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'Animals under wheels': Wildlife roadkill data collection by citizen scientists as a part of their nature recording activities

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Abstract

'Animals under wheels' is a citizen science driven project that has collected almost 90,000 roadkill records from Flanders, Belgium, mainly between 2008 and 2020. However, until now, the platform and results have never been presented comprehensively to the scientific community and we highlight strengths and challenges of this system. Data collection occurred using the subsite www.dierenonderdewielen.be ('animals under wheels') or the multi-purpose biodiversity platform observation.org and the apps, allowing the registration of roadkill and living organisms alike. We recorded 4,314 citizen scientists who contributed with at least a single roadkill record (207-1,314 active users per year). Non-roadkill records were registered by 85% of these users and the median time between registration of the first and last record was over 6 years, indicating a very high volunteer retention. Based on photographs presented with the roadkill records (n = 7,687), volunteer users correctly identified 98.2% of the species. Vertebrates represent 99% of all roadkill records. Over 145,000 km of transects were monitored, resulting in 1,726 mammal and 2,041 bird victims. Carcass encounter rates and composition of the top 10 detected species list was dependent on monitoring speed. Roadkill data collected during transects only represented 6% of all roadkill data available in the dataset. The remaining 60,478 bird and mammal roadkill records were opportunistically collected. The top species list, based on the opportunistically collected roadkill data, is clearly biased towards larger, enigmatic species. Although indirect evidence showed an increase in search effort for roadkill from 2010-2020, the number of roadkill records did not increase, indicating that roadkills are diminish-

ing. Mitigation measures preventing roadkill could have had an effect on this, but decrease in population densities was likely to (partially) influence this result. As a case study, the mammal roadkill data were explored. We used linear regressions for the 17 most registered mammal species, determining per species if the relative proportion per year changed significantly between 2010 and 2020 (1 significant decrease, 7 significant increases). We investigated the seasonal patterns in roadkill for the 17 mammal species, and patterns per species were consistent over the years, although restrictions on human movement, due to COVID-19, influenced the seasonal pattern for some species in 2020. In conclusion, citizen scientists are a very valuable asset in investigating wildlife roadkill. While we present the results from Flanders, the platform and apps are freely available for projects anywhere in the world.

Keywords
Citizen science, data quality, mammals, presence only data, relative trends, roadkill, structured monitoring, seasonal patterns

Introduction

Roads directly impact populations and species due to vehicle induced mortality. An estimated 29 million mammals and 194 million birds are killed annually on European roads (Grilo et al. 2020). Worldwide, all mortality sources considered, natural or human, vehicle induced mortality was 7% for adult mammals and 1% for adult birds (Hill et al. 2019).

Apart from direct mortality by wildlife vehicle collisions, roads and traffic do have multiple effects on ecosystems and wildlife populations including habitat loss and habitat fragmentation (Taylor and Goldingay 2010; Whittington et al. 2019). Roads can have genetic effects by acting as a barrier and decreasing genetic diversity (Coffin 2007;Holderegger and Di Giulio 2010). Furthermore, the presence of roads, and the intensity of their use, can result in behavioural changes of individuals and species (Mumme et al. 2000; Kerley et al. 2002; Whittington et al. 2019).

Monitoring of wildlife roadkill can, apart from the collection of the numbers being killed, facilitate monitoring of population trends, species distribution and invasions, animal behaviour and contaminants and disease (Schwartz et al. 2020). Volunteer citizen scientists can collect and/or process data as part of a scientific inquiry (Silvertown 2009) and they play an important role in the data collection of roadkill records in projects which have been initiated worldwide http://globalroadkill.net (Shilling et al. 2015). Globally, there are dozens of web based systems to register wildlife vehicle collision casualties or roadkill (Shilling et al. 2015). Citizen science data on roadkill has proven to be a valuable data source for the identification of potential roadkill hotspots (Shilling and Waetjen 2015; Périquet et al. 2018; Englefield et al. 2020), temporal patterns in roadkill (Raymond et al. 2021) and species range maps (Tiedeman et al. 2019). Long term motivation of volunteers, support for the identification of roadkill and feedback to volunteers are of critical importance in sustaining roadkill citizen science projects (Bil et al. 2020). The Flemish project 'Animals under wheels' (Dieren onder de wielen) is one of the largest citizen science driven roadkill databases

worldwide (Waetjen and Shilling 2017). However, until now, the platform and results have never been presented comprehensively to the scientific community. We highlight strengths and challenges of this system, which is easily and freely available to be deployed anywhere in the world for roadkill monitoring (and general biodiversity monitoring as well).

Methods

We describe and analyse the roadkill data submitted to the online biodiversity database https://waarnemingen.be, the local Flemish version of the international platform https://observation.org. This platform allows for the registration of observations of all plants, fungi and animals. Since the launch in 2008 until 2020, this resulted in more than 26,200 species and 31,5 million observations for the 13,522 km^2 of Flanders, generating one of the densest biodiversity datasets in the world. Flanders is the northern region of Belgium, situated in Western Europe. It has a very high human density of 487 inhabitants/km^2 (Statbel 2020) and 5.08 km of roads/km^2, one of the densest road systems in the whole of Europe (Vercayie and Herremans 2015). Flanders has 883 km of motorways, 6,040 km of regional roads and 64,080 km of local roads (FPS Mobility and Transport 2011). We show the 2019 traffic data since this is the last year without a COVID-19 impact. Daily, over 70 million vehicle kilometres are driven on Flemish motorways (Hoornaert 2019) and the monitoring of 880 motorway segments indicated an average daily traffic volume of 37,592 vehicles per segment per day (median = 32,067, min = 4,440 and max = 131,508) (Vlaams Verkeerscentrum 2021). On regional roads, the monitoring of 127 segments showed an average daily traffic volume of 17,583 vehicles per segment per day (median = 16,666, min = 2,381 and max = 36,649). For local roads, the authors are not aware of available data. The most recent available data from 2017 indicate the Flemish registered vehicles drive 61.1 billion kilometre per year (Kwanten 2018).

Roadkill data in the waarnemingen.be database can be submitted using: (a) the online platform https://waarnemingen.be, (b) the subsite www.dierenonderdewielen.be ('animals under wheels') or (c) the apps ObsMapp for Android, iObs for iPhone and recently ObsIdentify for all devices. On the online platform, the location of the observation must be pinpointed on the map, date/time selected and species and additional observation information 'roadkill' label must be selected using controlled vocabulary (Waetjen and Shilling 2017). In the apps, location and time are derived from the smartphone. Species and 'roadkill' must be selected using controlled vocabulary in the appropriate data fields. Photographs and additional information can be added to an observation but are not mandatory. The apps do also function in a voice recognition mode to register observations, which is always useful, but essential when monitoring during driving (Vercayie and Herremans 2015).

We analyse the number of users registering roadkill records, the active users per year and the number of new users per year (recruitment) to show the long-term vi-

ability of the project. We investigate the number of roadkill records per user and the distribution between users including the corresponding Gini coefficient, a measure of unevenness (0: totally equal, 1: a single person is responsible for all records) (Sauermann and Franzoni 2015). We calculate the retention time per user, defined as the time between the registration of the first and the last roadkill per user. For all roadkill registering citizen scientists, we examine if they also registered observations of plants, fungi or living wildlife within the waarnemingen.be database.

Data quality

Quality control of the data is an important step in all scientific processes, and also very important for citizen science projects (Wiggins et al. 2011). The data validation procedure in the 'waarnemingen.be'-database combines species specialists (experienced volunteers) assigning a validation status to observations and an algorithm automatically evaluating observations. This multi-step process depends on the proof presented (not mandatory but possible), species status (common vs rare), location and time (was there already a proven record of presence within a species group dependent defined range of space and time) of the observation (Swinnen et al. 2018). Species specialists can assign a validation status to an observation: (a) 'Approved (based on evidence)', evidence can be a picture or sound, (b) 'Approved (based on expert judgement)', the additional information or the knowledge of the observer makes it highly likely this is a correct observation, (c) 'Under review', temporary status, no decision has been taken yet, (d) 'Cannot be assessed', proof or explanation does not allow for a decision to be made, (e) 'Rejected', observation was wrong and user does not correct it. The algorithm can also assign a validation status: (f) 'Automatic validation', for a record to be automatically validated, there need to be a number of earlier observations of the species supported by proof (at least one or two), within a certain radius (ranging from 100 m to 10 km) within a specified time range (60–3000 days). Remaining observations are classified (g) 'unverified'. The validation process is an interactive process where users can be contacted for additional information or suggested to change the species name or other details in case of an error. We investigate the possible error ratio by calculating the percentage of approved observations (based on photographic evidence) which was initially wrong but corrected by the user after interaction with a validator.

Methodology of data collection

To allow standardised data collection and a quantifiable measure of search effort, two options for data registration are offered to users. In 2013, the option to gather standardised transect data was added to the website. Users were asked to choose a specific route, draw it online and check it at least once every two weeks, but not more than once a day. They were asked to fill in the survey, even if no roadkill was detected. These type of transects are called fixed transects in this manuscript. Since 2018, smartphone users can allow their app to register their transect while observing nature and register-

ing observations. When finished, users indicate per species group if their transect can be used as a roadkill monitoring transect. Since there are no requirements for transects to be identical, or to be repeated over time, we call them variable transects.

For the fixed transects, users register the transport modus (on foot, by bike, by car). For the variable transects, the transect is recorded by the smartphone and we derived the speed from the track length and duration, and classified transects as 0–7 km/h as on foot, 7–25 km/h by bike and >25 km/h by car (although another motorised vehicle is also possible). This distinction according to speed is important because speed affects detection probability and it is known that searching on foot is more effective than counting while driving (Slater 2002). Data collected during standardised monitoring contains more information but it is also more demanding for volunteers resulting in a smaller number of participants (Bonney et al. 2009).

Waarnemingen.be is mainly used as a personal notebook by naturalists to register and document their sightings. Although some users are aware of the additional scientific advantages standardised data collection offers, the majority of all observations in waarnemingen.be are presence only records (also known as roving records) (Vercayie and Herremans 2015). Given the correct identification of the species, presence is confirmed but search effort is unknown. The absence of a record can have multiple causes: no roadkill present, no observer present or both present but not registered by the observer. We show a summary of the transect data including transect characteristics and top 10 of recorded bird and mammal species and calculate the average distance that needs to be covered to encounter a roadkill. For the presence only data, a top 20 for bird and mammal casualties is presented and we compare the results with the data collected during transect counts. While herpetofauna is also an important species group, e.g. because of their worldwide threatened status (Heigl et al. 2017), we do not discuss them here since they are only recorded at lower driving speeds, and a larger (roadkill) database, separate from waarnemingen.be is available, calling for a specific analysis.

Case study: mammal roadkill records

The number of new observations (of all organisms) submitted to waarnemingen.be continues to increase year after year, from 400,000 in 2008 to over 6,000,000 in 2020 (and over 8.7 million in 2021). For 2010–2020 we investigate by means of a linear regression (R Core Team 2016): (a) is there an increase in mammal roadkill observations? (b) is there an increase in mammal observations (excluding all automated observations by camera traps and bat-detectors since they do not represent human search effort)? (c) are both correlated?

The large majority of roadkill data is collected as presence only data. Since search effort is unknown, absolute roadkill trends per species cannot be calculated. However, relative trends can be calculated and give an indication of the increase or decrease of roadkill abundance of a specific species compared to the other species killed on the road. For this analysis all mammal roadkill records were combined (presence only and transect data), excluding observations where observers indicated they were uncertain

of species determination (1.5% of observations), and only species with a minimum of 50 roadkill individuals were withheld, resulting in 17 species (only species level records were considered). Per species, the percentual abundance per year from these 17 species was calculated. By using a linear regression, we determine per species if the relative proportion per year changed significantly between 2010 and 2020. Graphs were made using ggplot 2 (R Core Team 2016; Wickham 2016). Based on unstructured, presence only, citizen science data on roadkill, we propose the relative change in proportion of roadkill victims as a means to gain insight in relative population changes as roadkill numbers are expected to be strongly and positively associated with the local abundance of living animals (Baker et al. 2004; George et al. 2011; Pettett et al. 2018; Schwartz et al. 2020).

Apart from the local abundance, timing within the year does influence the number of victims found. Animals are sensitive to wildlife vehicle collisions during movement. This can be daily movement while foraging or patrolling home ranges, or seasonality in mating, juvenile dispersal or migration (Taylor and Goldingay 2010; Garriga et al. 2017; Schwartz et al. 2020). For all roadkill data combined (presence only and transect data) we plot species specific density functions using ggplot 2 (R Core Team 2016; Wickham 2016). For this, the number of records was used, and not the number of individuals. Overall, 98.7% of records comprises a single individual, but more than one individual is also sometimes reported. This can reflect reality, multiple individuals killed at once or, sometimes, users combine a number of observations from a timespan from the same location and add a single observation to the database. Analysing these 'combination records' as if all individuals were killed at the same time would introduce errors in this seasonal pattern and to avoid this, the number of observations was used. For species with more than 1,000 records, we show the annual seasonal pattern in roadkill data. When fewer data are available, a single density plot combining the data from 2010–2020 is shown.

Results

Within Flanders, 89,276 roadkill records were registered from 1960–2020 (Fig. 1). Mammals (52,847), birds (23,346) and herpetofauna (11,762) represent 99% of roadkill observations. Coleoptera (n = 499) is the invertebrate group with the most roadkill records. One record can contain multiple individuals. Most records (93%) date from 2008 onwards, the launch of waarnemingen.be. The majority of 'historical' records (79%) were added by a single account (Regional Mammal Workgroup).

A total of 4,314 citizen scientists submitted at least one roadkill record from Flanders (Fig. 2). Male roadkill registering volunteers (1,547) are three times as abundant compared to females (457). For 2,310 citizen scientists the sex is unknown. On average 881 users were active per year (range 207–1,314) and this number shows a steady increase. Per year, on average 332 (range 207–465) 'new' users register their first roadkill victim with an increase of 20% in 2020 compared to the second best year (2009).

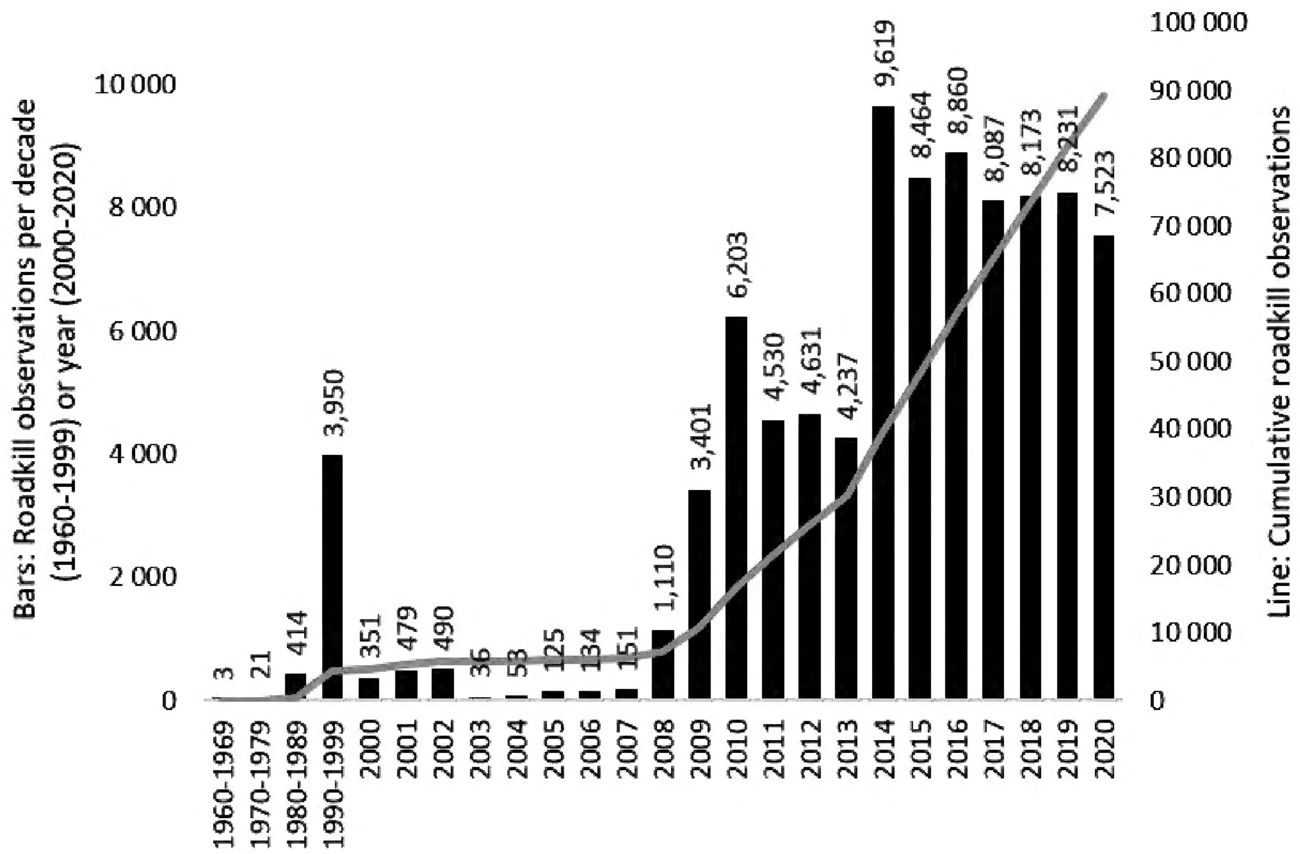

Figure 1. Roadkill observations per decade (1960-1999) or per year (2000-2020) and cumulative number of roadkill observations in Flanders, Belgium.

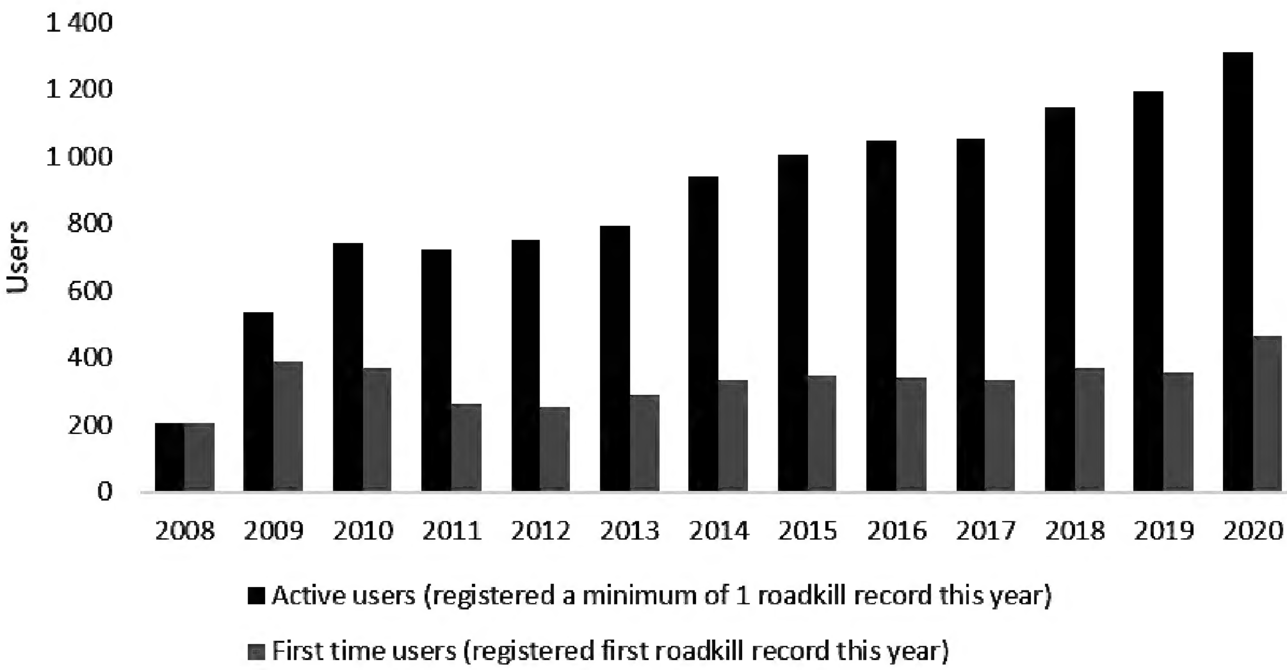

Figure 2. the number of active roadkill registering users per year in Flanders and the number of first time roadkill registering users per year in Flanders since 2008, the launch of https://waarnemingen.be until 2020.

Contributions of users are unequal with 44.4% of users only registering a single roadkill record (see Table 1). The median number of roadkill records per user is 2 (average 21, range 1–4,931). The Gini coefficient of inequality between users is 0.87.

When including all roadkill registering users, volunteer retention time, i.e. the median time between registration of first and last roadkill record, is 7 days. For users

Table 1. The amount of roadkill observations in 8 classes and the number of users in each class, including the percentage of users per class.

Roadkill observations	Users	% of users
1	1,914	44.4%
2-5	1,254	29.1%
6-10	368	8.5%
11-20	267	6.2%
21-50	258	6.0%
51-100	114	2.6%
101-500	109	2.5%
501-5000	30	0.7%

with only a single roadkill record, we consider this single record as the first and the last record and the time between records was 0 days. When excluding the users with only a single roadkill record, the median volunteer retention time increases to over 4 year (1,501 days).

The majority of roadkill recorders (85%) did also submit non-roadkill observations to the biodiversity database and together they are responsible for 25.9 million non-roadkill observations (on a total of 31.5 million non-roadkill records by 49,447 users registered in 2008–2020 in Flanders). This indicates that for most users, the registration of roadkill is a natural part of their registration of nature observations, but the focus is rarely on roadkill alone. When calculating the median volunteer retention time of citizen scientists which registered at least a single roadkill record, based on all of their observations, roadkill and living organisms together, this exceeds 6 years (2,318 days, range 0–5,243 days).

Data quality

In total, 38.9% of records were approved based on different procedures (Table 2). For all observations approved based on the presented photographic evidence, only 139 out of 7,687 recordings needed to be corrected by the validator. This results in an error rate of 1.8%. In only a very small percentage of cases, users do not respond to suggestions to change the species and the observation is then rejected.

All observations which were rejected, under review or which cannot be assessed are removed in the following analyses.

Table 2. Validation status of the roadkill recordings in Flanders (1960-2020).

Validation status	Number of observations (%)
Approved (based on evidence)	7,687 (8.61%)
Approved (based on expert judgement)	10,951 (12.27%)
Approved (automatic procedure)	16,062 (17.99%)
Under review	16 (0.02%)
Rejected	42 (0.05%)
Cannot be assessed	288 (0.32%)
Unverified	54,230 (60.74%)

Methodology of data collection

Transect data

We registered 309 fixed transects online since the start in 2013 until 2020. A little under half (148) were registered online but never monitored by the user. The remaining 161 transects were monitored at least once, resulting in 2,521 records of bird and mammal roadkill during 59,256 km of monitoring. In Table 3 we show the fixed transect characteristics and results grouped per transport mode.

We registered 4,778 variable transects for bird and mammal roadkill since 2018, the year when the smartphone applications (ObsMapp and iObs) allowed it, until the end of 2020. Each transect is considered unique since small variations in the registration of the transect are present, resulting in no repeated counts per transect. This resulted in 1,246 bird and mammal roadkill registrations while monitoring 86,235 km. In contrast with the fixed transects, it is possible the user only monitors a single species group. Therefore, mammal and bird transects are shown separately in Table 4.

When combining both transect types 3,767 roadkill records were registered. For birds, carcass encounter rates vary from 1 carcass per 75.7 km on foot, 1 carcass per 59.3 km by car to 1 carcass per 34.6 km by bike. For mammal, carcass encounter rates are similar, 1 carcass per 74.7 km on foot, 1 carcass per 70.7 km by car and 1 carcass per 43.5 km by bike. We show the top 10 of most frequently recorded (wild) roadkill species for birds and mammals while monitoring transects by car (Table 5) and bike (Table 6). We include observations not identified to species level, but they are unranked.

Table 3. Fixed transect characteristics and results grouped per transport mode (2013-2020). * A single transect can be monitored on foot, by bike and by car. That's why the sum of the different transects differs from 161.

	Distance (km)	Different transect*	# counts	Median # counts per transect	Average # counts per transect (range)	Roadkill Birds found	Roadkill Mammals found
By car	32,673	103	2,722	8	26 (1-484)	581	497
By bike	26,063	92	4,815	16.5	52 (1-1,204)	782	636
On foot	520	31	299	1	10 (1-70)	15	10

Table 4. Variable transect characteristics and results grouped per transport mode (2018-2020).

		Distance (km)	Different transects	Roadkill victims
By car	Birds	36,999	1,570	593
By car	Mammals	39,910	1,723	529
By bike	Birds	2,943	262	57
By bike	Mammals	3,137	285	35
On foot	Birds	1,600	461	13
On foot	Mammals	1,646	477	19

Table 5. Top 10 of birds and mammal roadkill victims encountered the most frequently by car during transect monitoring. Observations not identified to species level are shown but not ranked.

Birds	Scientific name	Common name	# ind.
1	*Columba palumbus*	Common wood pigeon	329
	Aves unknown	Bird unknown	286
2	*Turdus merula*	Common blackbird	172
3	*Phasianus colchicus*	Common pheasant	74
4	*Anas platyrhynchos*	Mallard	37
5	*Corvus corone*	Carrion crow	30
6	*Buteo buteo*	Common buzzard	20
7	*Pica pica*	Eurasian magpie	18
8	*Coloeus monedula*	Western jackdaw	17
9	*Gallinula chloropus*	Common moorhen	17
10	*Strix aluco*	Tawny owl	16
Mammals	**Scientific name**	**Common name**	**# ind.**
	Mammalia unknown	Mammal unknown	270
1	*Erinaceus europaeus*	Hedgehog	223
2	*Lepus europaeus*	European hare	97
3	*Rattus norvegicus*	Brown rat	79
4	*Oryctolagus cuniculus*	European rabbit	70
5	*Martes foina*	Beech marten	67
6	*Sciurus vulgaris*	Red squirrel	39
6	*Vulpes vulpes*	Red fox	39
8	*Mustela putorius*	European polecat	18
	Rattus unknown	Rat unknown	7
9	*Capreolus capreolus*	Roe deer	5
	Mustelidae unknown	Marten unknown	5
10	*Talpa europaea*	European mole	3

Table 6. Top 10 of birds and mammal roadkill victims encountered the most frequently by bike during transect monitoring. Observations not identified to species level are shown but not ranked.

Birds	Scientific name	Common name	# ind.
1	*Turdus merula*	Common blackbird	256
2	*Columba palumbus*	Common woodpigeon	169
	Aves unknown	Bird unknown	58
3	*Phasianus colchicus*	Common pheasant	46
4	*Anas platyrhynchos*	Mallard	28
5	*Coloeus monedula*	Western jackdaw	28
6	*Gallinula chloropus*	Common moorhen	24
7	*Passer domesticus*	House sparrow	24
8	*Erithacus rubecula*	European robin	23
9	*Streptopelia decaocto*	Eurasian collared dove	22
10	*Parus major*	Great tit	20
Mammals	**Scientific name**	**Common name**	**# ind.**
1	*Erinaceus europaeus*	Hedgehog	182
2	*Rattus norvegicus*	Brown rat	144
3	*Oryctolagus cuniculus*	European rabbit	71
4	*Lepus europaeus*	European hare	52
5	*Sciurus vulgaris*	Red squirrel	29
	Mammalia unknown	Mammal unknown	22
6	*Apodemus sylvaticus*	Wood mouse	14
6	*Martes foina*	Beech marten	14
	Muridae unknown	Mouse/rat unknown	12
	Soricidae unknown	Shrew unknown	12
8	*Talpa europaea*	European mole	11
	Rattus unknown	Rat unknown	10
	Rodentia unknown	Rodent unknown	10
	Microtidae unknown	Vole unknown	8
9	*Vulpes vulpes*	Red fox	6
10	*Crocidura russula*	Greater white-toothed shrew	5

Presence only data

A total of 20,638 bird victims and 39,849 mammal victims were registered in waarnemingen.be from 2010–2020. Consequently, 94% of all roadkill records from 2010–2020 are presence only data. We show the top 20 in Table 7.

Table 7. Top 20 of most registered bird and mammal roadkill victims which are collected as presence only records. Observations not identified to species level are shown but not ranked.

Birds	Scientific name	Common name	# ind.
1	*Turdus merula*	Common blackbird	3,686
2	*Columba palumbus*	Common woodpigeon	3,624
3	*Anas platyrhynchos*	Mallard	1,411
4	*Phasianus colchicus*	Common pheasant	1,294
5	*Tyto alba*	Western barn owl	926
6	*Strix aluco*	Tawny owl	817
	Aves unknown	Bird unknown	766
7	*Gallinula chloropus*	Common moorhen	761
8	*Buteo buteo*	Common buzzard	728
9	*Pica pica*	Eurasian magpie	504
10	*Passer domesticus*	House sparrow	404
11	*Coloeus monedula*	Western jackdaw	402
12	*Athene noctua*	Little owl	333
13	*Corvus corone*	Carrion crow	267
14	*Streptopelia decaocto*	Eurasian collared dove	248
15	*Asio otus*	Long-eared owl	234
16	*Erithacus rubecula*	European robin	213
17	*Garrulus glandarius*	Eurasian jay	212
18	*Falco tinnunculus*	Common kestrel	194
19	*Larus argentatus*	European herring gull	193
20	*Turdus philomelos*	Song thrush	175
Mammals	**Scientific name**	**Common name**	**# ind.**
1	*Erinaceus europaeus*	Hedgehog	12,147
2	*Vulpes vulpes*	Red fox	5,353
3	*Sciurus vulgaris*	Red squirrel	3,779
4	*Martes foina*	Beech marten	3,619
5	*Mustela putorius*	Western polecat	2,591
6	*Oryctolagus cuniculus*	European rabbit	2,569
7	*Lepus europaeus*	European hare	2,148
8	*Rattus norvegicus*	Brown rat	2,108
9	*Capreolus capreolus*	Roe deer	855
	Mammalia unknown	Mammal unknown	488
10	*Talpa europaea*	European mole	317
	Mustelidae unknown	Marten unknown	287
11	*Meles meles*	Eurasian badger	283
12	*Mustela nivalis*	Least weasel	232
13	*Mustela erminea*	Stoat	186
	Martes foina/martes	Beech/Pine marten	171
14	*Sus scrofa*	Wild boar	137
	Rattus unkown	Rat unknown	74
15	*Castor fiber*	Eurasian beaver	67
16	*Martes martes*	Pine marten	65
17	*Apodemus sylvaticus*	Wood mouse	63
18	*Crocidura russula*	Greater white-toothed shrew	59
19	*Pipistrellus pipistrellus*	Common pipistrelle	46
20	*Mus musculus*	House mouse	40

Mammal case study

We compare the number of non-roadkill mammal observations (one observation can contain multiple individuals) with the number of mammal roadkill observations (transect and present only data combined) annually from 2010–2020 in Flanders, Belgium (Table 8).

Over the years, there is a significant increase in non-roadkill mammal observations (slope = 9106, t = 4.49, p-value = 0.00150**) but no significant increase in roadkill registrations (slope = 118, t = 1.88, p-value = 0.09). There is also no significant correlation between non-roadkill and roadkill mammal observations (slope = 0.008, t = 1.379, p-value = 0.201).

Table 9 shows the 17 mammal species with more than 50 roadkill individuals, the outcomes from the linear regression between year (2010–2020) and the percentual abundance per year.

Table 8. Mammalian roadkill and non-roadkill observations per year and the percentage of roadkill compared to all mammal observations from 2010-2020 in Flanders. Obs.= observations.

Year	Mammal roadkill obs.	Non-roadkill mammal obs.	Mammal roadkill as % of total mammal obs.
2010	3,338	20,201	14.2%
2011	2,740	21,100	11.5%
2012	2,884	30,009	8.8%
2013	2,639	27,211	8.8%
2014	4,836	46,033	9.5%
2015	4,212	35,815	10.5%
2016	4,408	51,417	7.9%
2017	3,866	108,415	3.4%
2018	4,040	123,193	3.2%
2019	4,312	73,858	5.5%
2020	3,580	88,850	3.9%

Table 9. Outcome of the linear regression for the 17 most registered mammal species in Flanders from 2010-2020. Significant codes in the p-value column: <0.1 . >0.05, <0.05 * > 0.01, <0.01 ** > 0.001, <0.001 *** For common names, see Table 7.

Rank	Species	N	slope	Std. error	t-value	p-value
1	*Erinaceus europaeus*	12,262	-0.051	0.325	-0.158	0.878
2	*Vulpes vulpes*	5,193	-0.467	0.230	-2.029	0.073 .
3	*Sciurus vulgaris*	3,769	0.047	0.131	0.358	0.728
4	*Martes foina*	3,566	0.425	0.121	3.526	0.006 **
5	*Oryctolagus cuniculus*	2,578	-0.339	0.170	-1.994	0.077 .
6	*Mustela putorius*	2,514	-0.450	0.129	-3.500	0.007 **
7	*Rattus norvegicus*	2,268	0.141	0.159	0.884	0.400
8	*Lepus europaeus*	2,252	0.269	0.089	3.013	0.015 *
9	*Capreolus capreolus*	798	0.147	0.046	3.165	0.012 *
10	*Talpa europaea*	328	0.023	0.024	0.961	0.362
11	*Meles meles*	275	0.119	0.035	3.431	0.007 **
12	*Mustela nivalis*	226	-0.004	0.012	-0.342	0.740
13	*Mustela erminea*	185	-0.004	0.013	-0.306	0.767
14	*Sus scrofa*	103	0.057	0.009	6.007	0.0002 ***
15	*Apodemus sylvaticus*	74	0.020	0.004	5.389	0.0004 ***
16	*Castor fiber*	60	0.041	0.010	3.797	0.004 **
17	*Martes martes*	57	0.028	0.014	1.995	0.077 .

Graphs showing percentual abundance per year per species are shown in Appendix A. *Mustela putorius* is the only species with a significant decreasing relative trend from 2010–2020. There are seven species with an increasing relative trend, ordered here from steepest to gentlest slope: *Martes foina*, *Lepus europeaus*, *Capreolus capreolus*, *Meles meles*, *Sus scrofa*, *Castor fiber* and *Apodemus sylvaticus*. Graphs showing seasonal patterns in relative density per species for each year (2010–2020) are added to Appendix B. Seasonal patterns in roadkill recordings differ clearly from species to species with most species showing a bi- or unimodal pattern. When comparing the pattern from a single species over multiple years, the consistency within the patterns is (very) good. Also the species with fewer observations show mostly a clear seasonal pattern.

Discussion

The detected and registered roadkill observations are only the tip of the iceberg. Even a structured daily roadkill census underestimates the death rate (of smaller victims) with a factor 12–16 (Slater 2002). Apart from the effect that roadkill has on wildlife (populations) there is also an economic cost. There are no numbers available for Flanders, or the whole of Europe, but wildlife-vehicle collisions in Spain cost 105 million € yearly (Sáenz-de-Santa-María and Tellería 2015) while the animal-vehicle accidents with ungulates in Sweden resulted in a cost of 275 million € in 2015 (Gren and Jägerbrand 2019).

For Flanders, *Capreolus capreolus*, *Sus scrofa*, *Canis lupus* and *Castor fiber* are among the heaviest wild mammals, but injury or even death of drivers or passengers can also occur when crashing into, or trying to avoid, smaller animals (Langbein 2007). A better understanding of roadkill is therefore in the best interest of wildlife and humans.

The amount of roadkill records increased heavily since the launch of https://waarnemingen.be in 2008 and together, over 4,300 citizen scientists collected almost 90,000 roadkill records. Similar to crowd science user contribution patterns, a small number of users contributed most of the recordings and the Gini coefficient of 0.87 is very similar to the average crowd science Gini coefficient of 0.85 Sauermann and Franzoni (2015) calculated for 7 crowd science projects. The registration of roadkill seems to be an integrated part of the nature observation and registration, for most volunteers, since 85% of users did also register non-roadkill observations. The use of a multi-purpose biodiversity platform has a positive effect on the retention time, which is over 6 years for roadkill recorders in waarnemingen.be. This long volunteer retention time indicates that allowing the registration of all species groups, roadkill or not, using the tools the users are already familiar with, is a successful alternative, and possibly even preferable to a single purpose data platform focussing on roadkill alone.

Some scientists may be sceptical about the data quality of records collected by citizen scientists, although they have the potential to produce data with an accuracy at least equal to professionals (Kosmala et al. 2016). We report a species identification accuracy of roadkill recordings with photographs of 98% (n = 7,687) which is nearly identical to the 97% presented by Waetjen and Shilling (2017). This high propor-

tion of correct species identification is an indication of the quality of the database. However, we suspect species identification accuracy to be lower for records without photographs since many of these identifications are from driving vehicles. Although more than 60% of observations are unverified, the majority of these observations are 'common' species, which are mainly registered by a limited group of experienced nature observers, and there is no reason to assume 'a priori' that these records contain more errors. Depending on the purpose of the analysis, different data selections can be made but the increase in data quality by eliminating all possible errors does not always compensate for the loss in data quantity (Van Eupen et al. 2021). Continuous communication on the importance of photographs when registering roadkill aims to increase the amount of verifiable records in the future.

Differences in the most registered species depending on data collection method

In order to determine which species is killed the most in traffic, standardised monitoring is necessary. Our results indicate that for birds and mammal species, searching at an intermediate speed from 7 to 25 km/h results in the highest number of carcasses found. This is somewhat unexpected given that a slower speed should increase detection rates (Slater 2002). We suggest that the searching for roadkill carcasses was fitted into the routine of a number of people in the past years and that biking happens more frequently next to busy roads, where more carcasses are present compared to walking, which is more likely along calmer roads. Driving by car resulted in roughly the same encounter rates of birds and mammals carcasses compared to walking, however due to the higher speed, corpses not identified to species level are more numerous. Stopping safely to identify the species is often not possible in Belgium and stopping on motorways is forbidden (and dangerous) (minimum speed 70 km/h, maximum speed 120 km/h). At this speed, identification at species level is frequently impossible.

The quality of transect data (with a standard protocol) is higher but it is more difficult to find volunteers to collect them (Bonney et al. 2009; Vercayie and Herremans 2015). As a consequence, they only represent 6% of all available roadkill data from Flanders. Although informative for local situations, currently, this is too sparse for region-wide analysis. The variable transects are promising in this respect because they can be monitored anywhere and anytime, but they are currently not yet widely enough adopted by the user community. It is also too early for a detailed analysis since they were only launched in 2018. Additional promotion and awareness in the user community of the applicability could boost the popularity of these variable transects.

There is a clear difference between the rank list of most observed species during transects and the rank list of most observed species in the opportunistic data. When comparing data collected by car and bike, it is clear that only larger species are registered from cars and a higher proportion was not identified on species level. For the mammal data, all rank lists of most observed species are led by Hedgehogs (with the exception of unidentified mammals which outrank them in species lists collected from cars). Hedgehogs are frequently reported as traffic victims in Western Europe (Huijser

and Bergers 2000; Pettett et al. 2018) and road mortality of Hedgehogs is expected to be an important factor in their decline (Wright et al. 2020). Common blackbirds are ranked third by monitoring from the car, but first in the other lists. This is not unexpected since they had the highest predicted roadkill rate, 12 individuals/km/year, in the model of Grilo et al. (2020) and are among the most frequently killed bird species in Western Europe (Erritzoe et al. 2003). Even transect data must be interpreted with care. Carcass persistence times and detection depend on size, with smaller animals being removed faster by scavengers (Santos et al. 2011; Teixeira et al. 2013; Ratton et al. 2014). Detection probability of larger mammals can also be influenced since they are more likely to be removed by maintenance workers or during police intervention at the site of an accident. Data collected by these services can be an important addition to the data collected by citizen scientists. Although proven to be a valuable data source (Grilo et al. 2009) additional steps need to be taken in Flanders to collect and centralise this data.

As expected, the ranking of victims collected as presence only data differs from the rankings in the transect data: presence only data show a clear bias to larger species, but possibly also species which are perceived as more interesting. Number two in the presence only data ranking is Red fox, which ranks only 6th in transects by car, and 9th in transects by bike. Foxes are infrequently seen alive, so, an encounter with a dead fox is for many people special enough to report. The number three, Red squirrel ranked 6th in transects by car and 5th in transects by bike. The Brown rat, the species encountered most frequently as roadkill (with exception from the Hedgehog) in transects by bike was only ranked 8th in the presence only data list. This indicates that due to reporting bias the presence only data should not be used to determine which species are killed the most in traffic.

Mammal case study

From 2010–2020 there is a strong increase in the number of non-roadkill mammal observations registered on waarnemingen.be but no significant increase in registered roadkill mammal observations. It is known that retention of volunteers can be challenging (Pocock et al. 2014; Shilling et al. 2015, 2020) but the number of observers registering roadkill has never been higher than the past 3 years (see Fig. 2) and their retention time on the waarnemingen.be platform exceeds 6 year. Volunteer participation depends also on repeated communication about the project. Over the last 3 years, our own communication channels mentioned the project 'animals under wheels' in 23 newsletters, we provided 15 contributions to written magazines, made 2 promotion videos and contributed to 10 national symposiums. Mainstream media wrote 47 articles about the project, and we gave 20 radio and 3 TV interviews (overview in Jacobs et al. (2021)) on the subject. This indicates that the absence in increase in registered roadkill mammals is not due to a reduction in observers/search effort but we believe that this is a strong indication that the number of roadkill is diminishing. Additional standardised collected data could confirm/refute this hypothesis. If this reduction is caused by effective road mitigation such as fencing, when possibly combined with crossing structures or animal detection systems (Rytwinski et al. 2016) this reduction does not

reflect a decrease in population but a decrease in wildlife victims due to the mitigation measures. However, it might also reflect a reduction in abundance of (a number of) mammal species in Flanders that are most prone to being killed by vehicles.

Our species specific linear regression models indicate that 8 out of 17 mammal species have a significant change in proportion of roadkill victims through time. The number of reported roadkill victims of *Mustela putorius*, the Western polecat, declines, with the steepest significant slope of all species (slope = -0.450). The polecat is suspected to be in decline in Belgium, and also in most neighbouring countries (Croose et al. 2018) and there are indications this decline was already present from 1998–2010 (Van Den Berge and Gouwy 2012).

The proportion of victims of the seven other species are increasing over the years. Two species are (recently) recolonising (parts of) Flanders after a period of absence: Eurasian beaver (Swinnen et al. 2017) and Wild boar (Rutten et al. 2019). Roe deer has increased in range and numbers significantly since the 70's (Casaer and Huysentruyt 2016), Beech marten, is doing the same the last decades (Van Den Berge 2016) and more recently, Badgers are also expanding from their last stronghold (Van Den Berge et al. 2017). Although the increase in population density is not quantified, we assume that this translates in higher relative roadkill numbers. The increase of the Eurasian hare was unexpected since the species was recently added as vulnerable to the red list of the Netherlands (bordering Flanders) (van Norren et al. 2020). However, for Flanders no monitoring scheme is in place. For Wood mouse we have no knowledge of population monitoring. This is a small-bodied species resulting in low carcass retention times (Santos et al. 2011; Ratton et al. 2014) and they were recorded relatively infrequently indicating that these results have to be interpreted cautiously. Remarkable is that the number of reported European hedgehog roadkill remains stable from 2010–2020. Until 2018, a strong decrease was occurring, but in 2019 and 2020 the proportion abruptly increased and was again at the 2010 level. This increase is currently unexplained but a fast recovery of the populations seems unlikely. There are reports of an unknown disease the last few years in Hedgehogs, possibly this also influences behaviour and making Hedgehogs more sensitive to being killed by cars.

Species distribution maps can be consulted at www.waarnemingen.be and additional info in Verkem et al. (2003). Linear regression models were also performed for the period of 2010–2019 since the global pandemic of the coronavirus disease (COVID-19) in 2020 resulted also in Flanders in confinement measures which are expected to have affected the search effort and the number of animals killed (Bíl et al. 2021; Driessen 2021). All trends remained similar, with the exception of the European hare, where the increase became non-significant.

Although the seasonal patterns are based on the rough data, without any correction for search effort within or between years, patterns of the same species are (highly) consistent. We expect that the large amount of data smoothens smaller inter- and within-year variation in search effort of individual observers. However, major events are detectable. In Flanders, there was a strict ban on non-necessary (car)travel from the 18th of March 2020 to the 8th of June 2020 due to the COVID-19 pandemic. Apart from the lives of wildlife this would have saved (Bíl et al. 2021; Driessen 2021), also

very few observers were on the road to quantify this effect. Determining which of both factors was the most important is not possible using presence only data. For species in which the peak period of kills overlaps with the confinement measures, such as Western polecat, the seasonal pattern of 2020 is clearly affected. Knowing the roadkill patterns can help to protect specific species of interest by using specific warning signs, and (temporal) road closure can even increase habitat quality (Whittington et al. 2019). Although no age or sex of the individuals was recorded in most cases, most peaks in roadkill density are presumed to be linked to increased movement because of mating or juvenile movements and dispersal (Carvalho et al. 2018; Raymond et al. 2021).

We show that roadkill monitoring using citizen scientists can generate informative results. However, this is not the endpoint. Data collected during the 'animals under wheels' project also contributed to the mitigation of local mortality hotspots. Furthermore, the data can be consulted by policy makers and a number of questions were asked in the Flemish Parliament concerning wildlife roadkill, indicating that the problem is acknowledged at the political level.

Conclusion

Large quantities of roadkill records are collected by citizen scientists in Flanders, Belgium. Volunteers remain engaged for a long period of time, probably due to the use of a multi-purpose platform which also allows the registration of living organisms. Species identification accuracy is high. Data collected using a standardised protocol is present, however, data quantities are currently too low for nation-wide analysis. Currently, 94% of all roadkill data are presence only records. Our results indicate that the amount of mammal roadkill is diminishing in Flanders, possibly due to mitigation measures or due to reduced population densities. We show that the citizen science data can be used to detect trends in percentual abundance of roadkill per species per year and to show seasonal patterns in relative roadkill density. Additional research to identify and consequently mitigate roadkill hotspots, minimise and correct for biases and the comparison between roadkill and population trends remains to be done. An increased effort to convince observers to collect standardised transect data and photographs of roadkill will increase the value of the dataset even further. We conclude that citizen scientists are playing an important role in roadkill research and will continue to do so in the future.

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Appendix A

For the 17 mammal species with more than 50 roadkill individuals, we show the linear regression figures between year (2010–2020) and the percentual abundance per year. Significant regressions are shown with a black line, non-significant with a grey line.

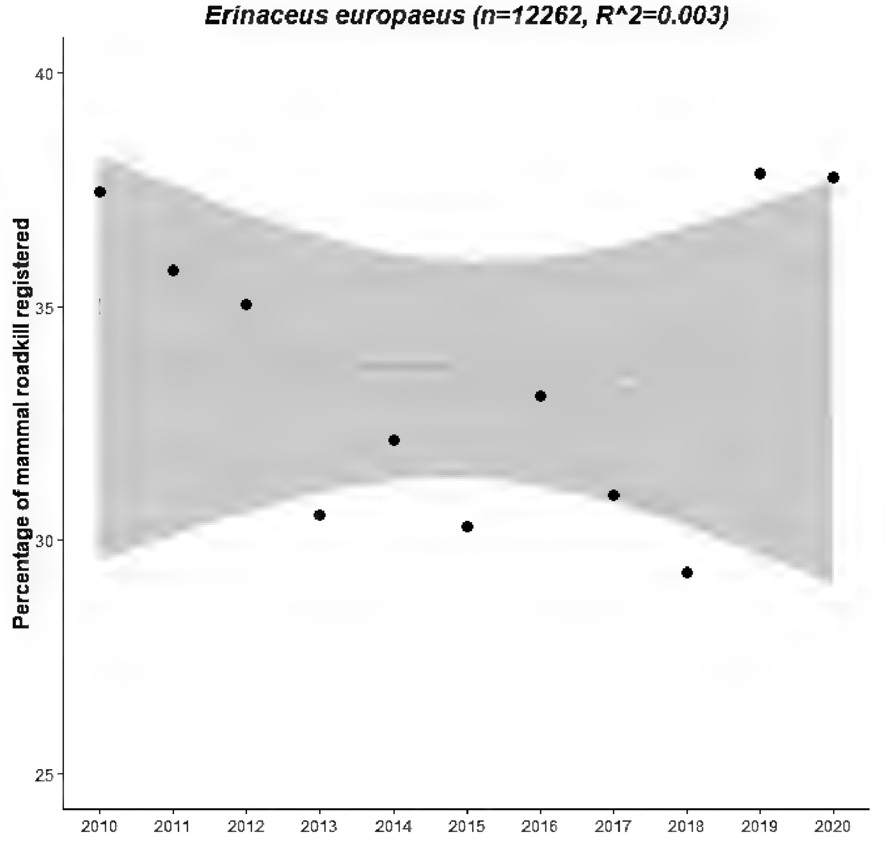
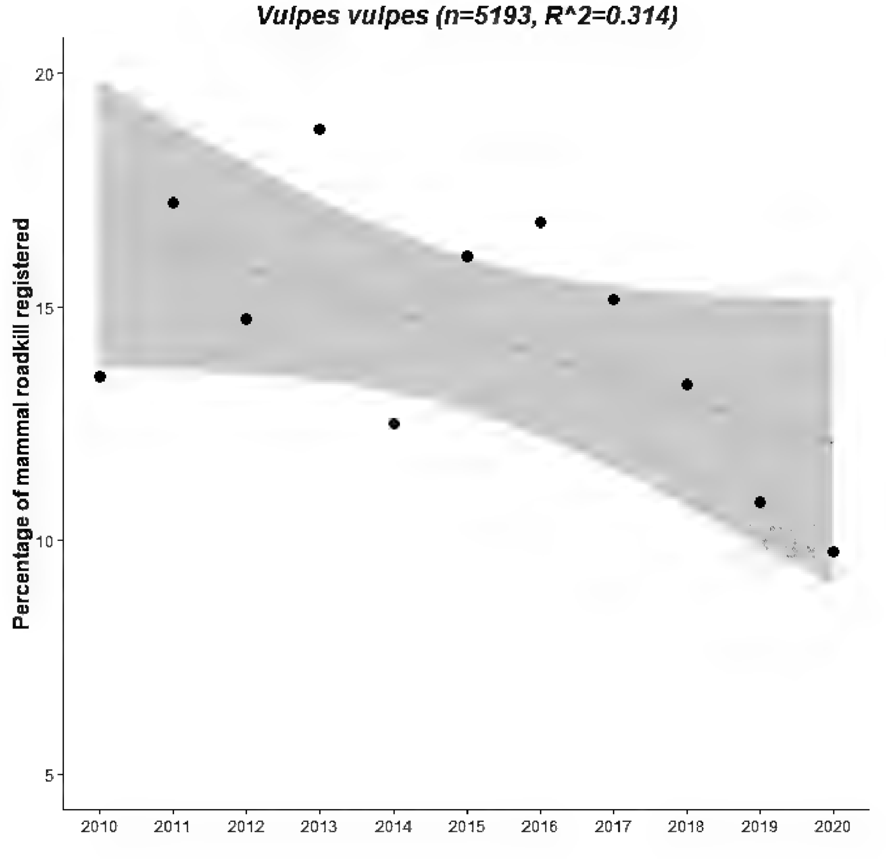


Figure A1.



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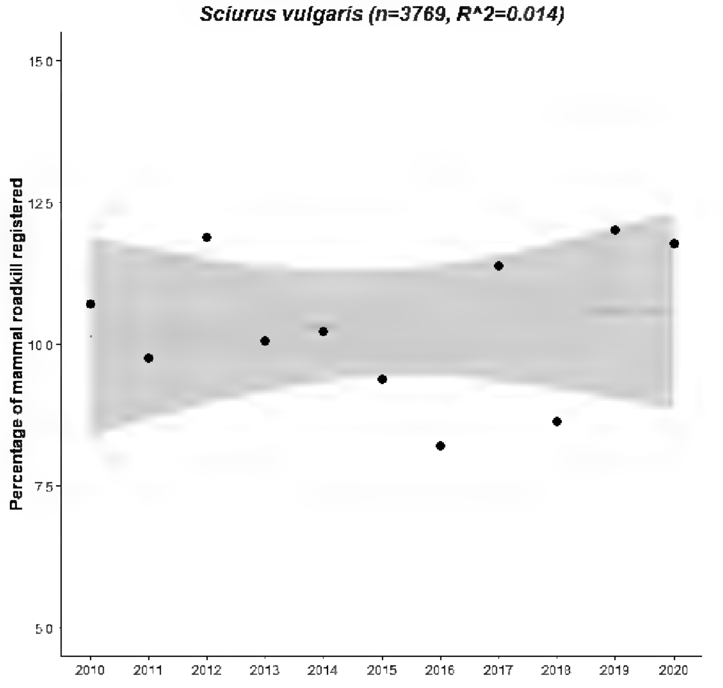

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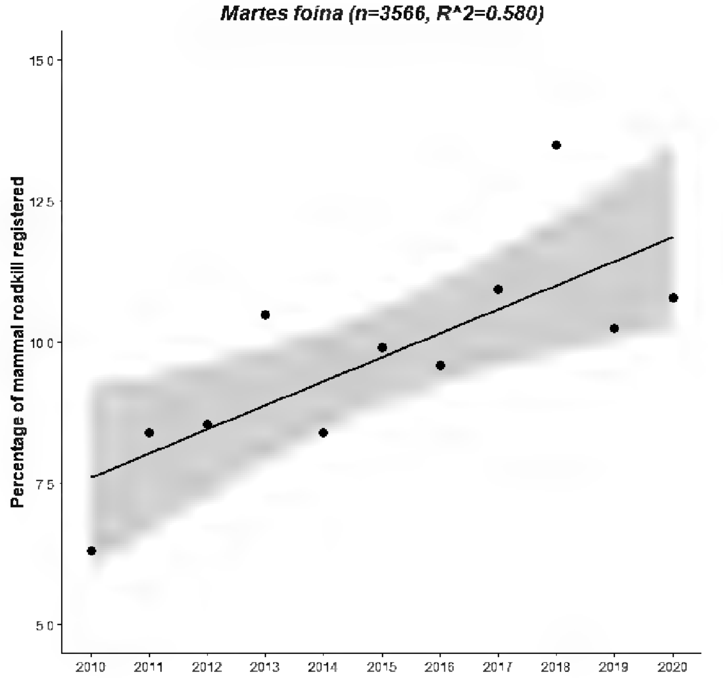

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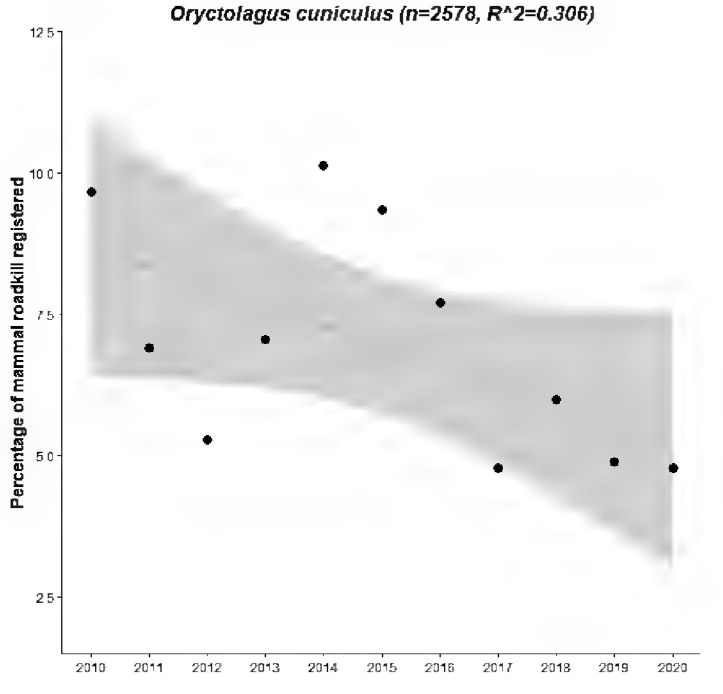

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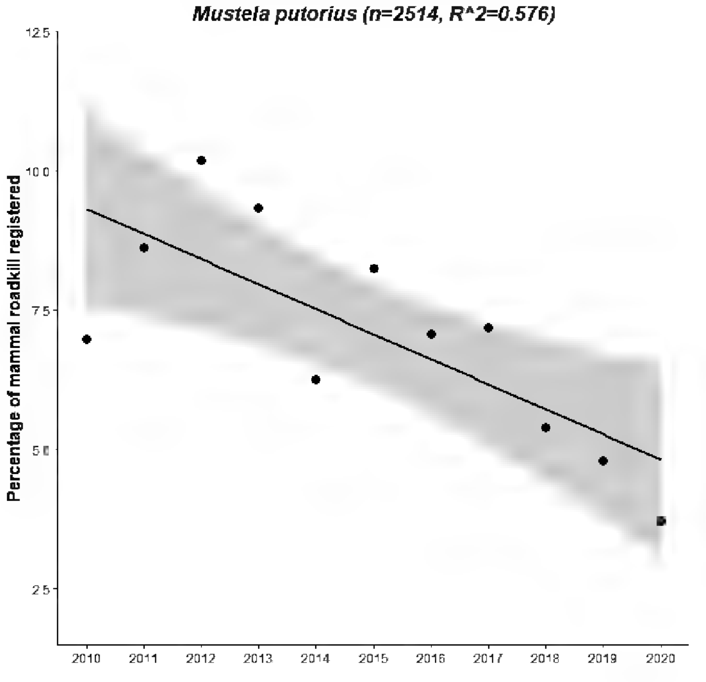

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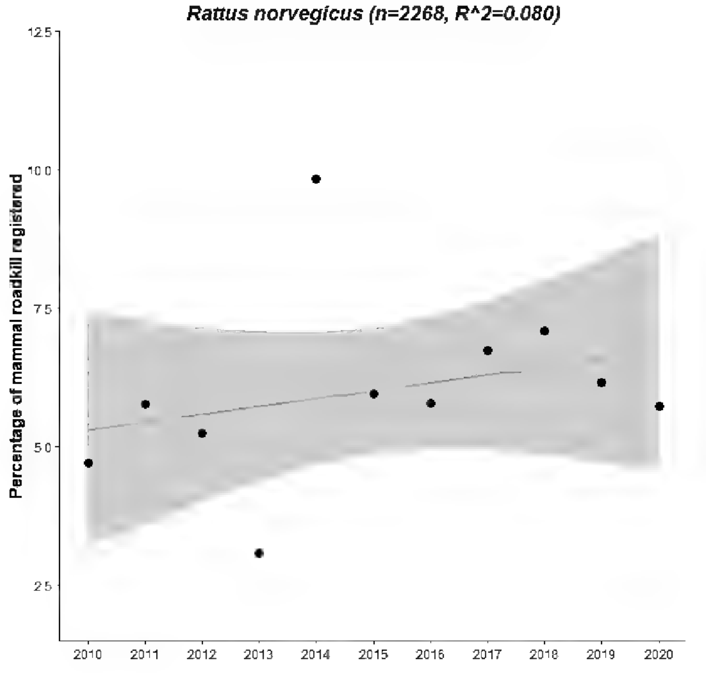

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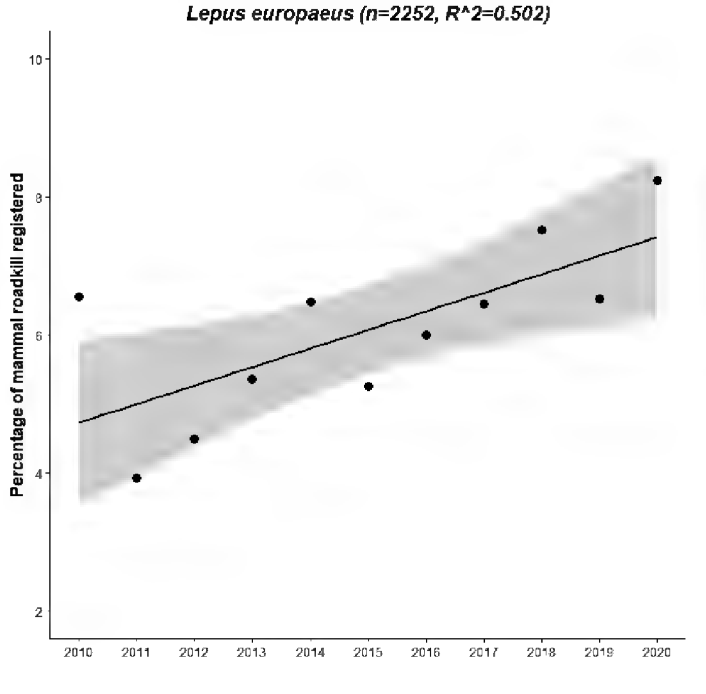

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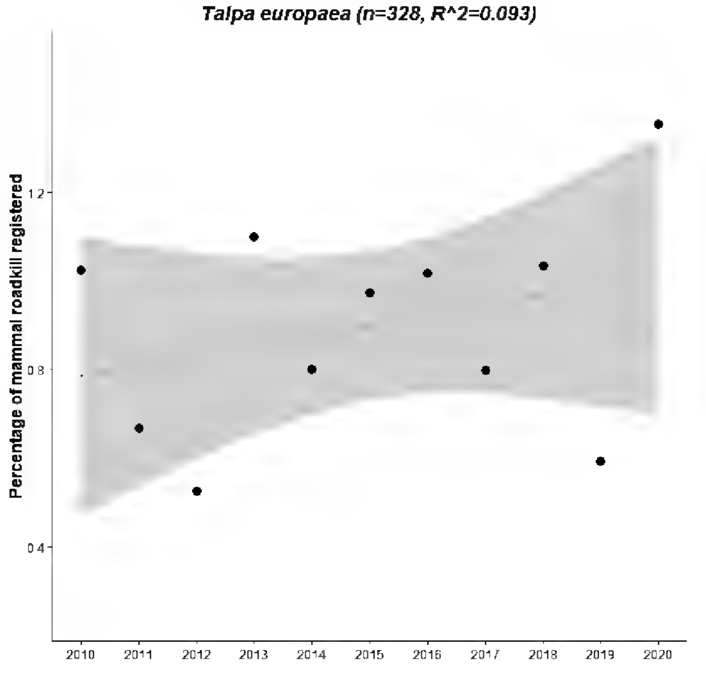

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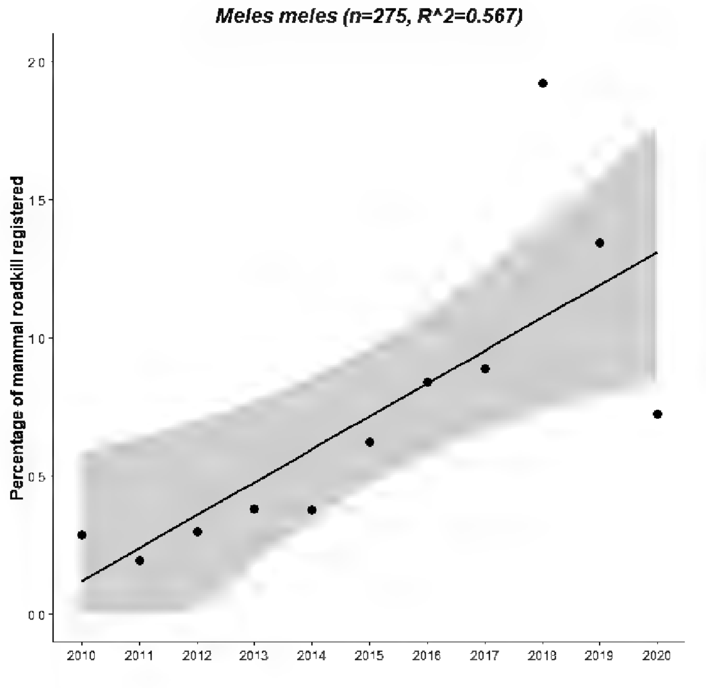

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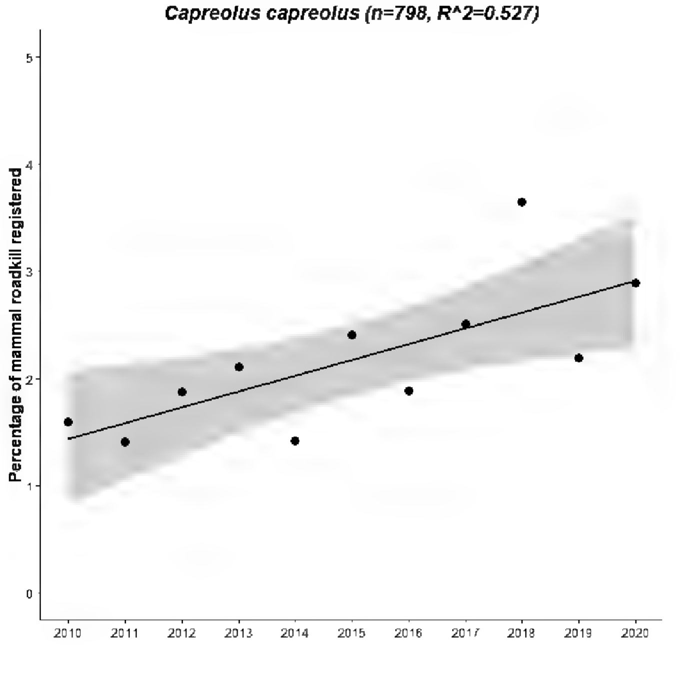

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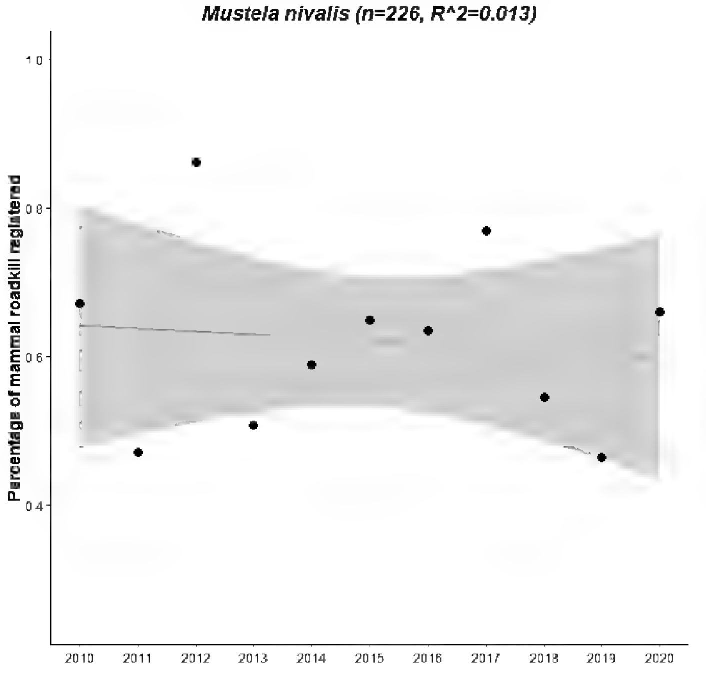

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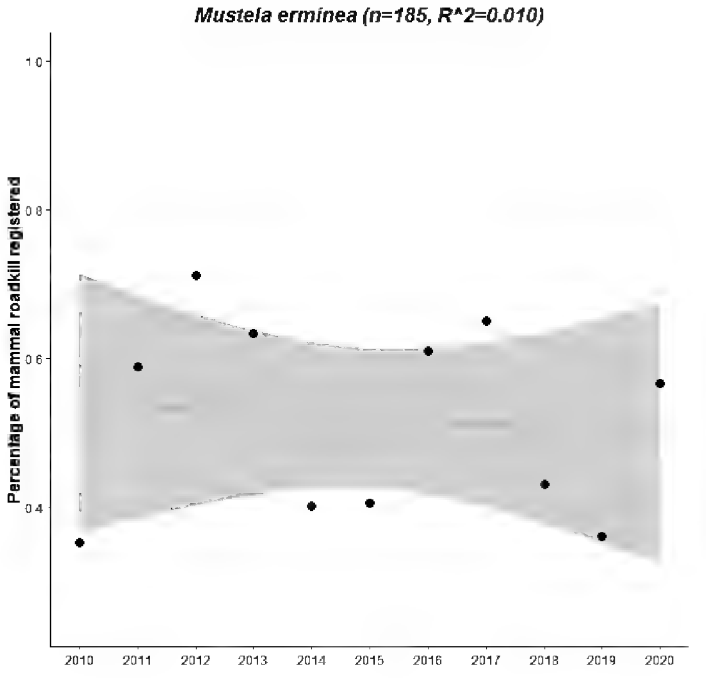

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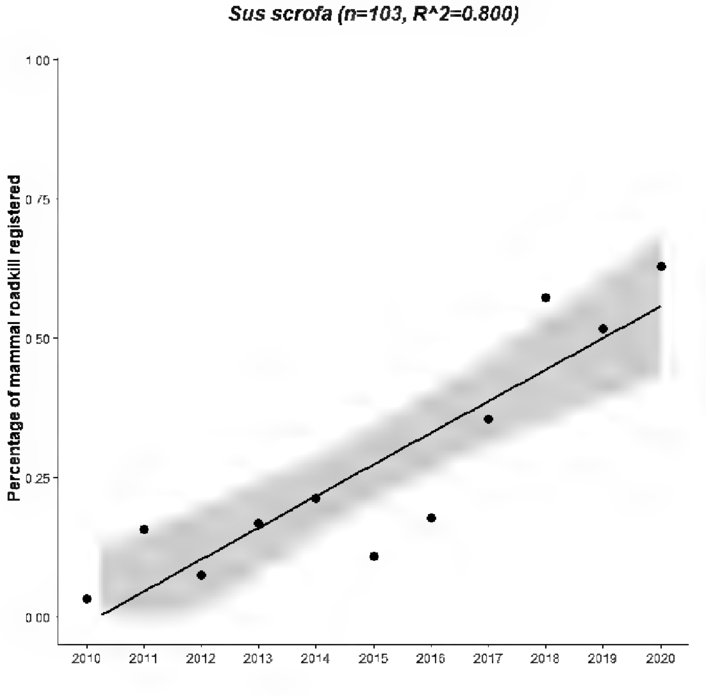

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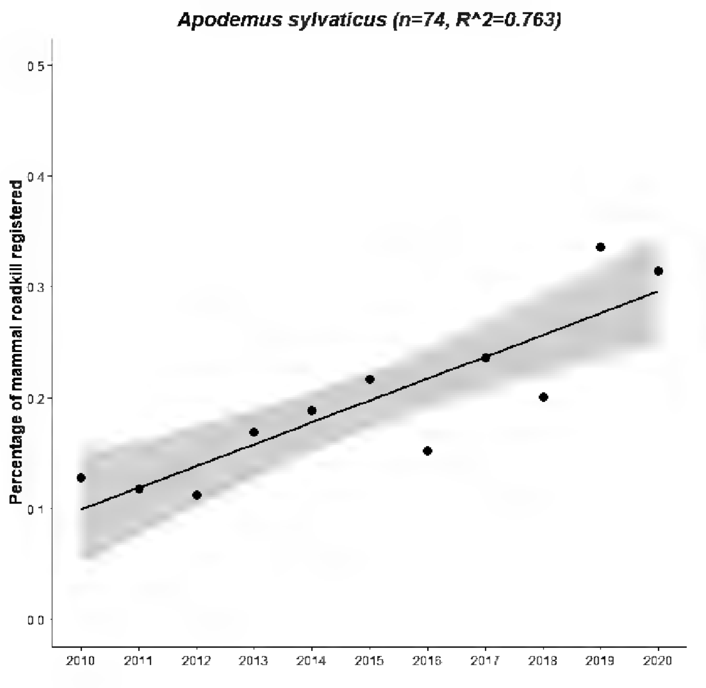

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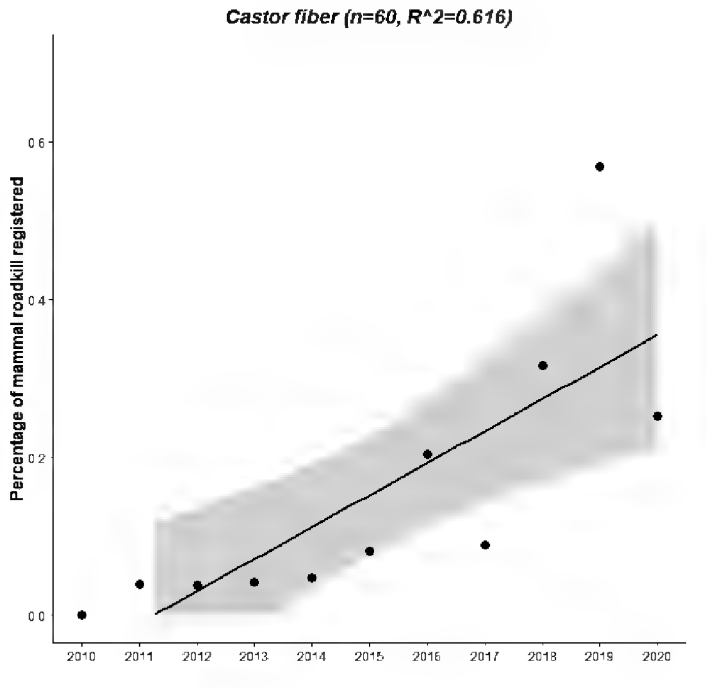

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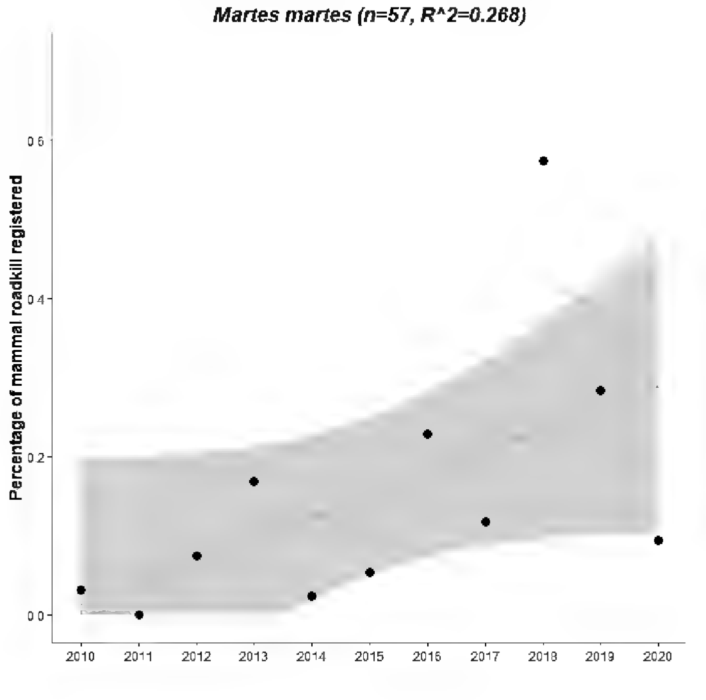

Figure A17.

Appendix B

For the 17 most recorded mammal species we show the variation in the roadkill pattern within Flanders. For species with more than 1000 recordings, we show the pattern of each individual year (2010-2020). For species with fewer than 1000 recordings all data are combined to generate a general pattern.

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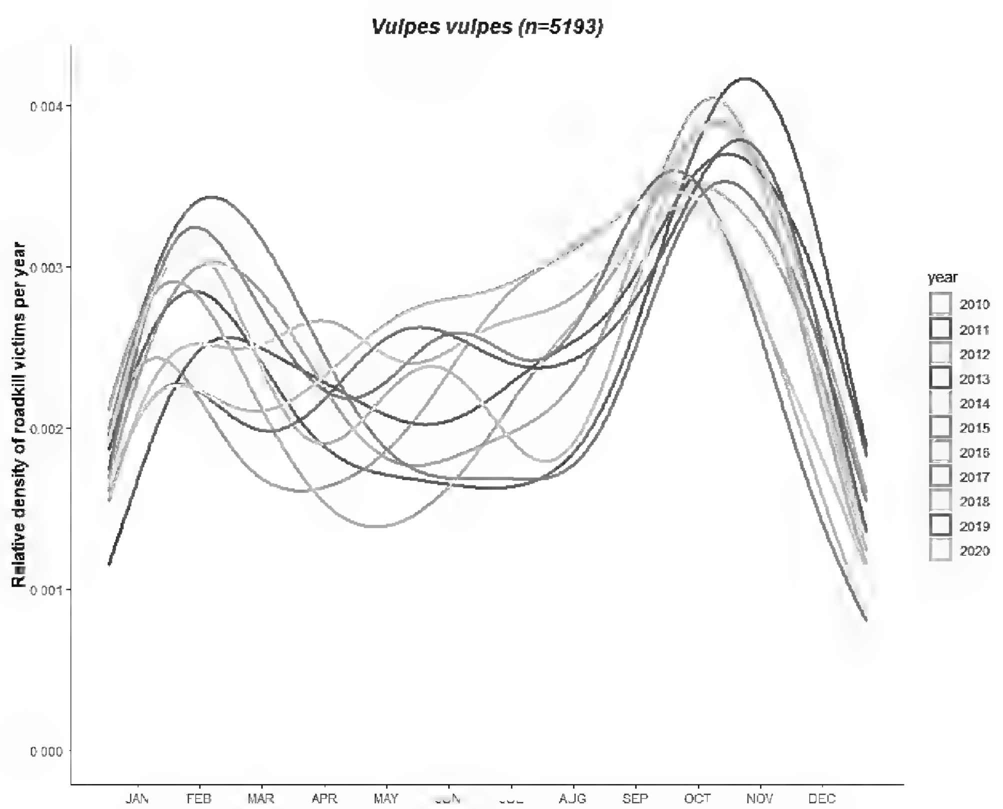

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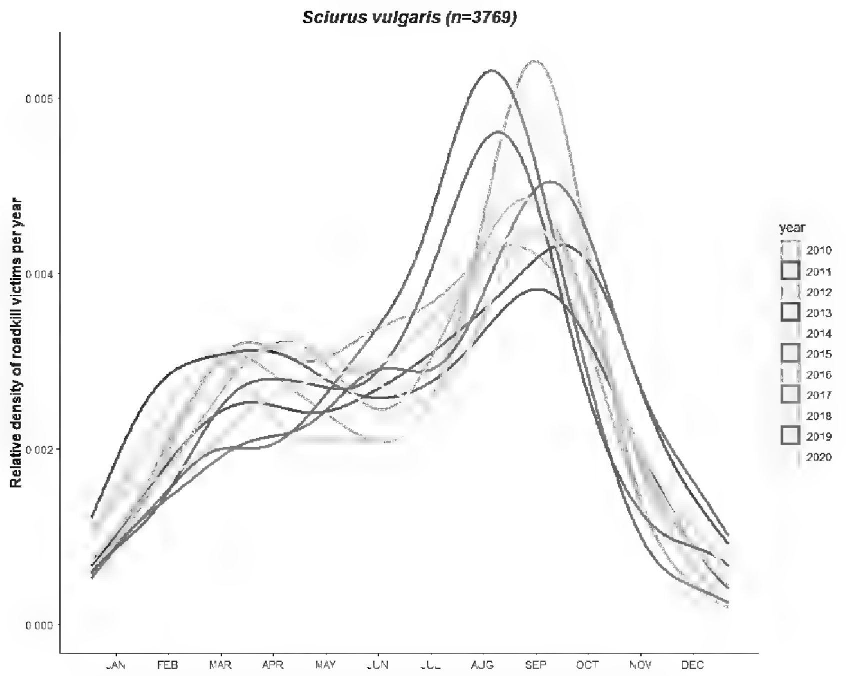

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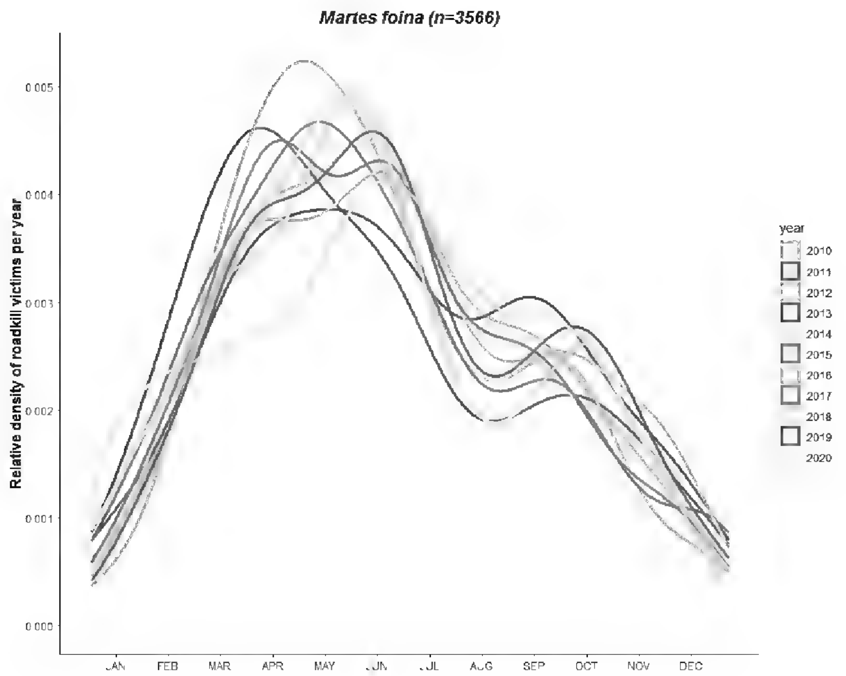

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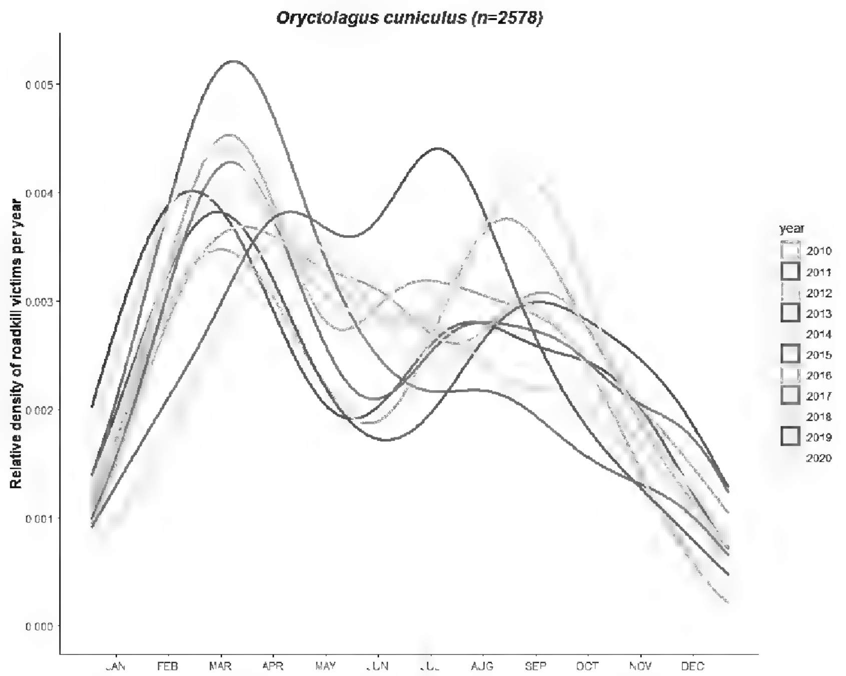

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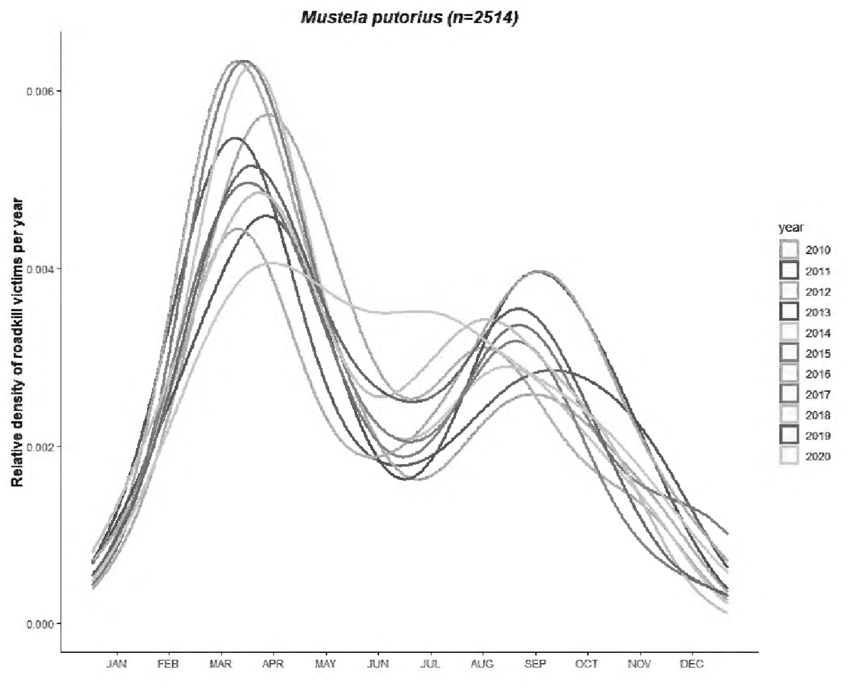

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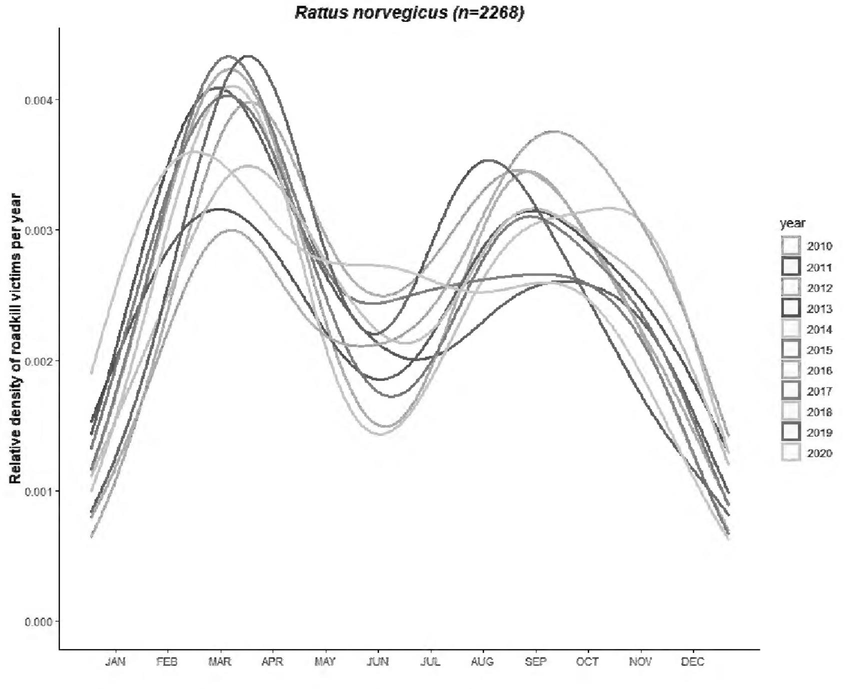

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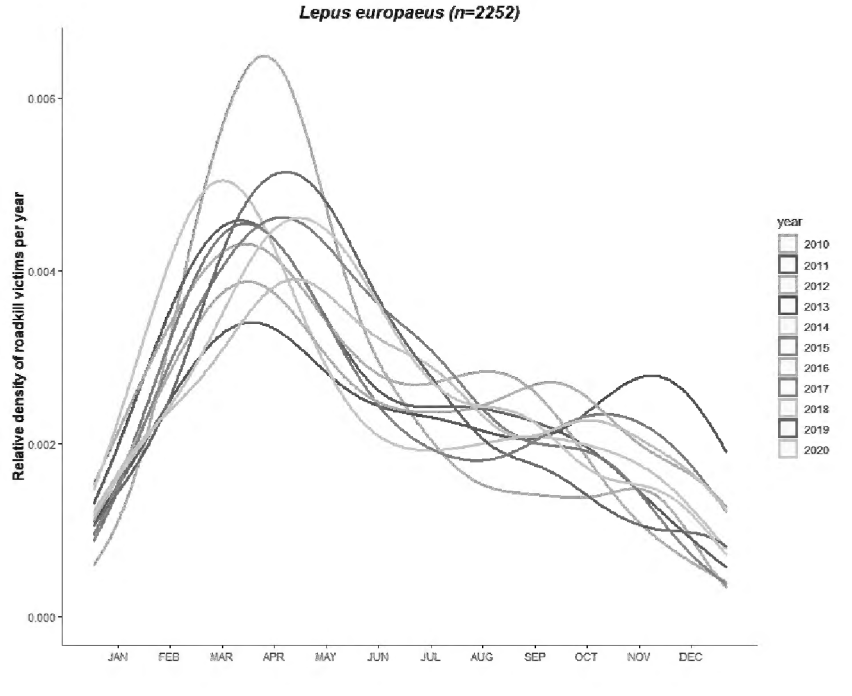

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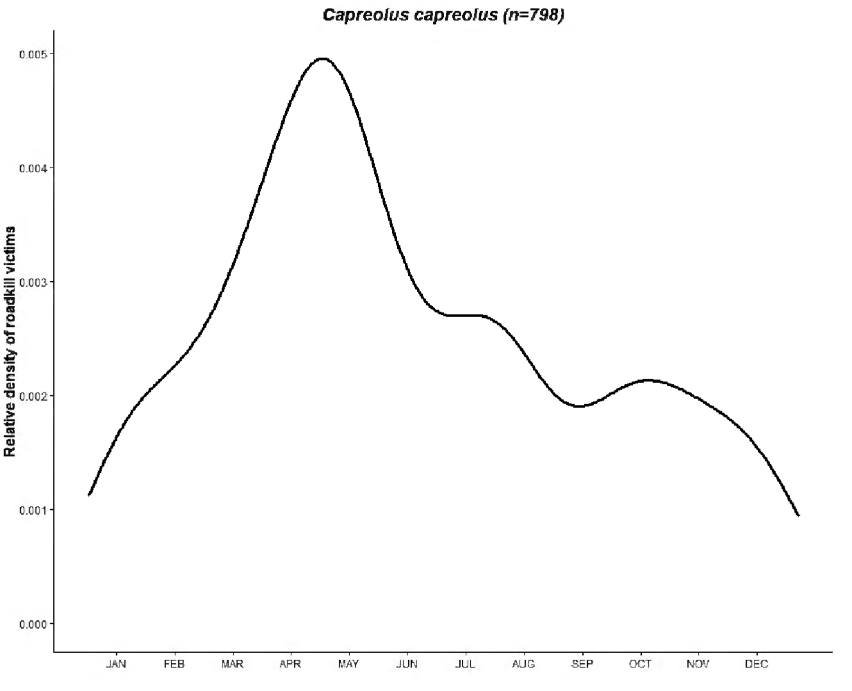

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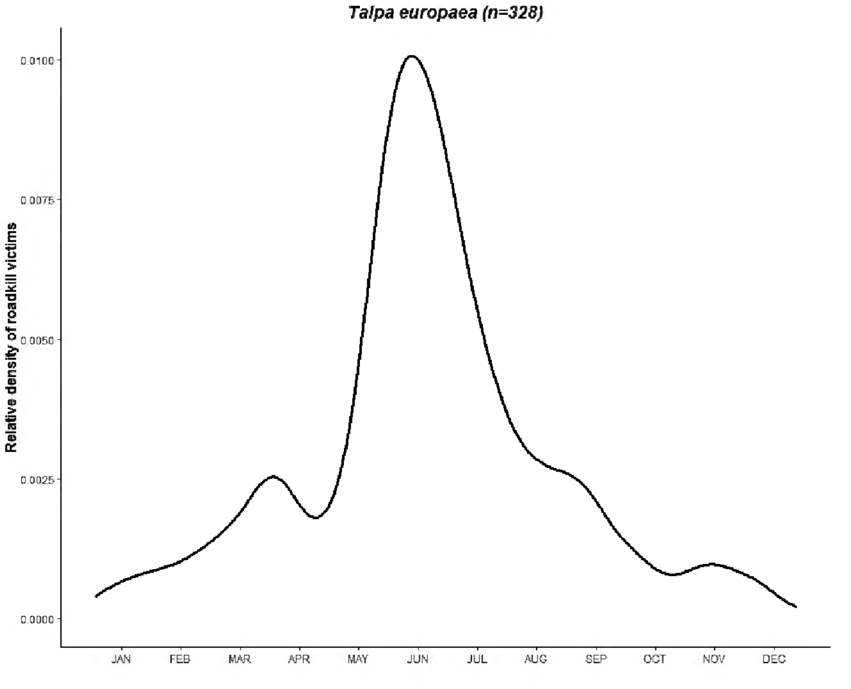

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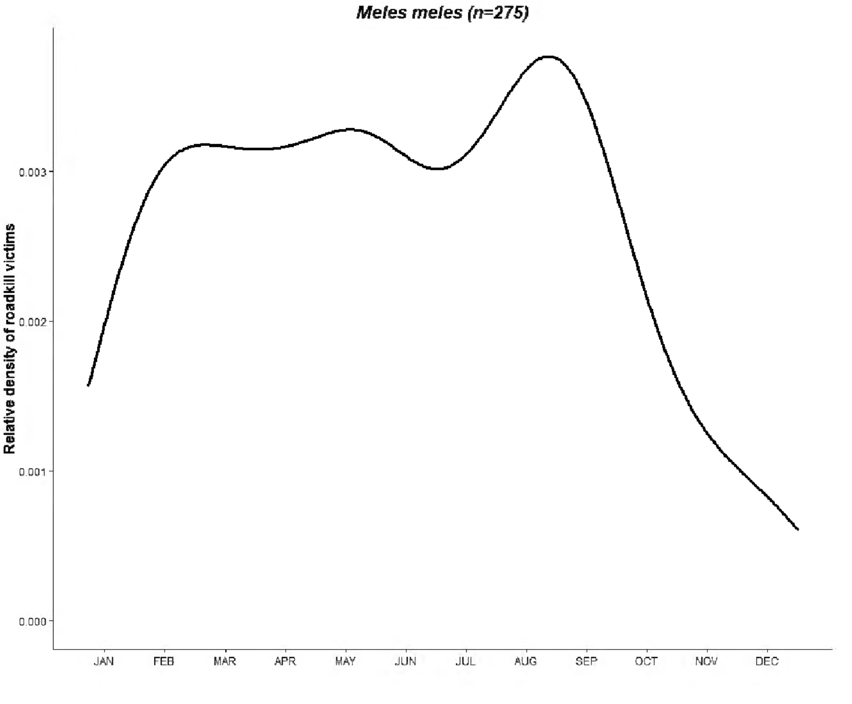

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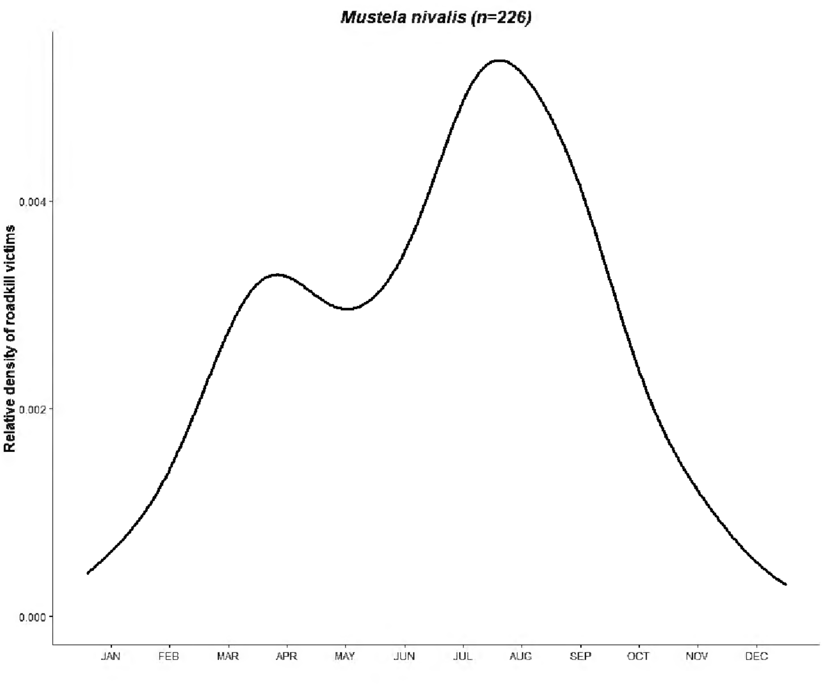

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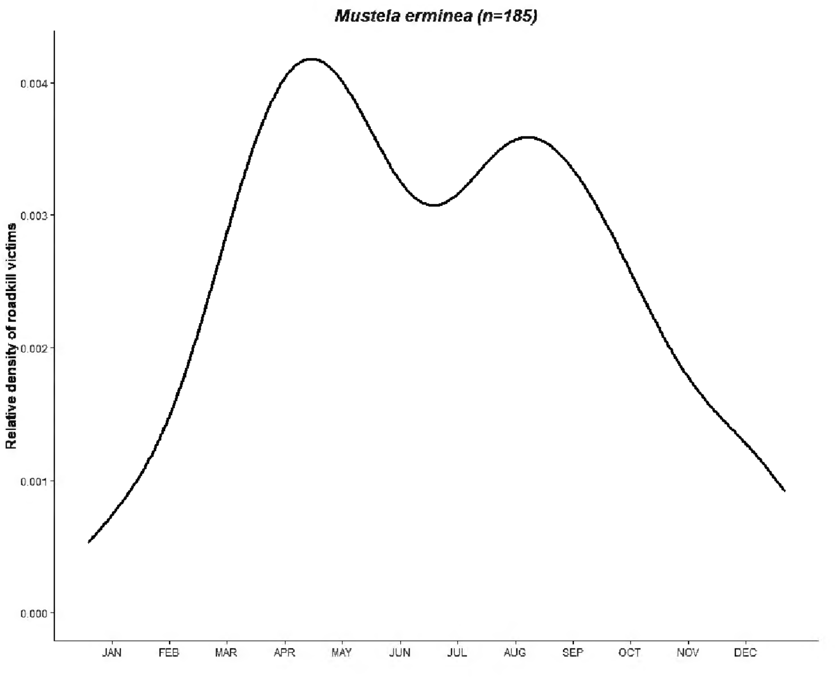

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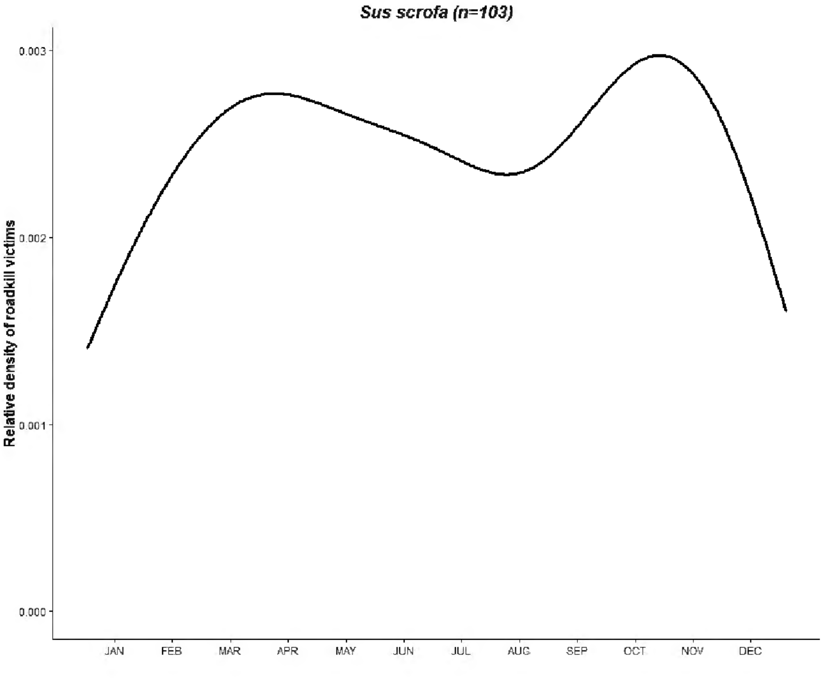

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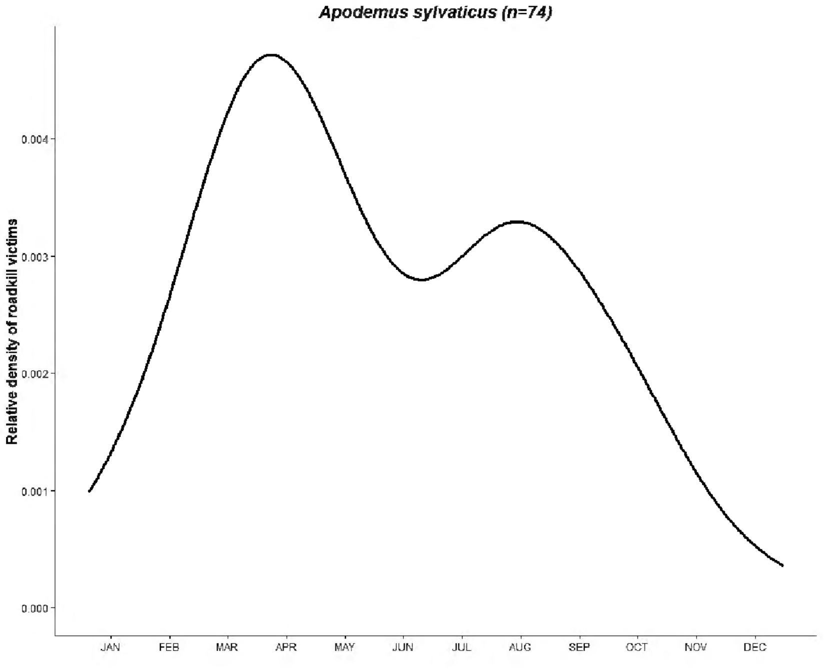

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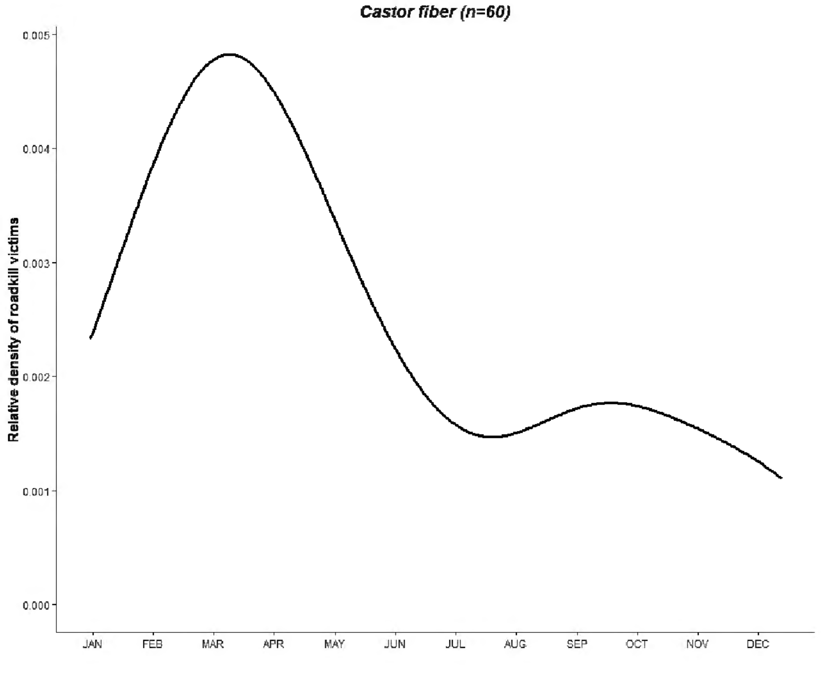

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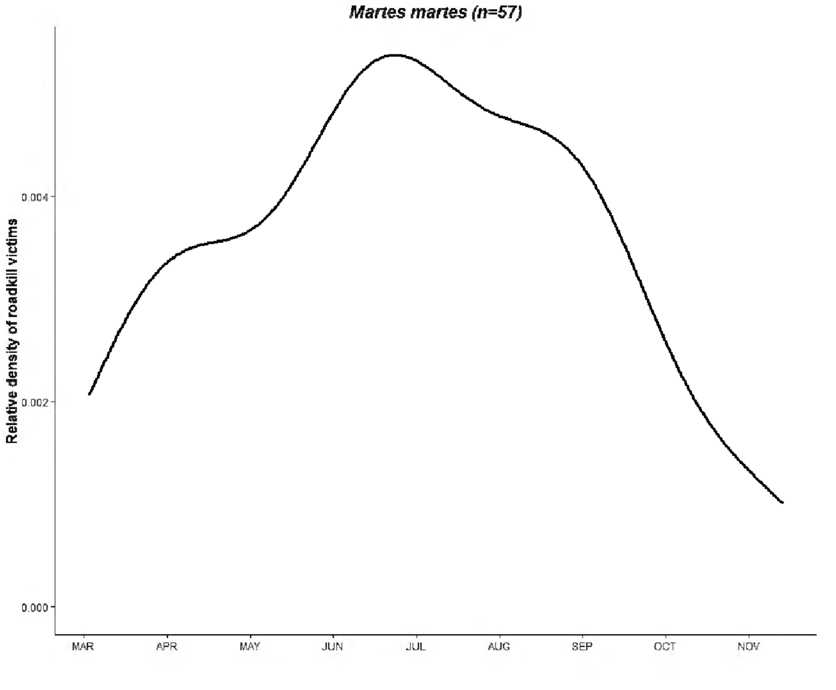

Figure B17.